Int J Life Cycle Assess (2012) 17:635–645
DOI 10.1007/s11367-012-0383-1

CARBON FOOTPRINTING

Carbon footprint of spring barley in relation to preceding oilseeds and N fertilization

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Received: 27 August 2011 / Accepted: 14 January 2012 / Published online: 15 February 2012

Abstract
Purpose Carbon footprint of field crops can be lowered through improved cropping practices. The objective of this study was to determine the carbon footprint of spring barley (*Hordeum vulgare* L.) in relation to various preceding oilseed crops that were fertilized at various rates of inorganic N the previous years. System boundary was from cradle-to-farm gate.
Materials and methods Canola-quality mustard (*Brassica juncea* L.), canola (*Brassica napus* L.), sunflower (*Helianthus annuus* L.), and flax (*Linum usitatissimum* L.) were grown under the N fertilizer rates of 10, 30, 70, 90, 110, 150, and 200 kg N ha^{-1} the previous year, and spring barley was grown on the field of standing oilseed stubble the following year. The study was conducted at six environmental sites; they were at Indian Head in 2005, 2006 and 2007, and at Swift Current in 2004, 2005 and 2006, Saskatchewan, Canada.
Results and discussion On average, barley grown at humid Indian Head emitted greenhouse gases (GHGs) of 1,003 kg CO_2eq ha^{-1}, or 53% greater than that at the drier Swift Current site. Production and delivery of fertilizer N to farm gate accounted for 26% of the total GHG emissions, followed by direct and indirect emissions of 28% due to the application of N fertilizers to barley crop. Emissions due to N fertilization were 26.6 times the emission from the use of phosphorous, 5.2 times the emission from pesticides, and 4.2 times the emission from various farming operations. Decomposition of crop residues contributed emissions of 173 kg CO_2eq ha^{-1}, or 19% of the total emission. Indian Head-produced barley had significantly greater grain yield, resulting in about 11% lower carbon footprint than Swift Current-produced barley (0.28 vs. 0.32 kg CO_2eq kg^{-1} of grain). Emissions in the barley production was a linear function of the rate of fertilizer N applied to the previous oilseed crops due to increased emissions from crop residue decomposition coupled with higher residual soil mineral N.
Conclusions The key to lower the carbon footprint of barley is to increase grain yield, make a wise choice of crop types, reduce N inputs to crops grown in the previous and current growing seasons, and improved N use efficiency.

Keywords Carbon footprint · Life cycle assessment · N use efficiency · No-till practices

Responsible editor: Matthias Finkbeiner

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1 Introduction

Rising awareness of climate change and energy security has spurred the interest of quantifying carbon footprints of goods and services for all sectors (Wiedmann et al. 2006).

In agriculture, the carbon footprint of grain crops is considered a new farm management indicator and can be the focal point in the evaluation of environmental impacts of agricultural activities (Weinheimer et al. 2010). Improved farming practices are required to minimize potential negative impacts of agricultural activities on environments (Liebig et al. 2007). In recent years, best crop management practices have been developed for not only producing high-quality, affordable food in sufficient quantity, but also reducing negative environmental impacts. One of the promising practices is to adopt diversified cropping systems where cereals, oilseeds, and legume crops are arranged in well-designed crop sequences (Gan et al. 2010). Studies from the northern Great Plains of North America have shown that the diversification of cropping systems can reduce production inputs (Zentner et al. 2001), decrease pest infestation (Krupinsky et al. 2002; O'Donovan et al. 1997), and lower carbon footprints of field crops (Gan et al. 2011c).

Spring barley (*Hordeum vulgare* L.) is a main feed grain crop typically grown in diversified cropping systems in rotation with other crops (Karamanos et al. 2010). In semiarid rainfed environments, barley crop usually follows an oilseed crop such as flax (*Linum usitatissimum* L.), sunflower (*Helianthus annuus* L.), or *Brassica* species such as *Brassica juncea* mustard, *Brassica napus* canola or *Brassica rapa* canola. The production of these oilseeds often requires high N fertilizer input in order to optimize seed yield and oil quality (Malhi et al. 2007; May et al. 2010). Under favorable growing conditions, canola crops respond positively to N fertilizer up to 180 kg N$\,$ha^{-1}, and some hybrid cultivars can respond to N fertilizer up to 250 kg N$\,$ha^{-1} (Brandt et al. 2007). Even in semiarid areas where water is the primary factor limiting crop production, a level of 100 kg N$\,$ha^{-1} of fertilization often results in high economic return for hybrid *Brassica* crops (Karamanos et al. 2007; Malhi et al. 2007; Cutforth et al. 2009).

Little has been determined whether the high level of fertilizer N input in the previous oilseeds would affect the carbon footprint of the subsequent barley crop. There exist huge knowledge gaps on the comparative values of carbon footprints of barley crops grown under various cropping systems. The present study may generate valuable information to begin to fill the knowledge gap. Therefore, the objectives of this study were to determine (1) the carbon footprint of barley preceded by various oilseed crops that were fertilized at various rates of inorganic N fertilizers the previous years and (2) the effect of environmental conditions on the carbon footprint of barley under semiarid rainfed conditions. We hypothesized that the type of oilseed crops grown the previous season and N fertilizer input to the previous oilseeds impacted the carbon footprint of the subsequent barley crop, and that the degree of the influence interacted by environmental conditions under which the crop was grown.

2 Materials and methods

2.1 Field experiment

Field experiments were conducted at six environsites (i.e., the combinations of two locations × 3 years); they were at Indian Head in 2005, 2006 and 2007, and at Swift Current in 2004, 2005 and 2006, Saskatchewan, Canada. The soil characteristics of the experimental locations are summarized in Table 1. Treatments included the main plot, four oilseed species in the previous year, and the subplot, seven rates of N fertilizer applied to the previous oilseeds. Canola-quality mustard (cv. Dahinda), *B. napus* canola (cv. Invigor 5020), sunflower (cv. 63 M02), and flax (cv. CDC Bethune) were grown in a factorial combination with N rates of 10, 30, 70, 90, 110, 150, and 200 kg N$\,$ha^{-1}, using a randomized, complete block design with four replicates. The oilseed crops were managed using recommended practices in terms of seeding techniques and pest control, etc. (May et al. 2010). In the following year, spring barley (cv. Metcalf) was planted on the fields of standing oilseed stubbles. In each year, a different piece of land was used for the oilseed–barley sequencing plots. At Indian Head, barley was planted on 5 May, 6 May and 12 May, in 2005, 2006, and 2007, respectively, and at Swift Current on 27 April, 5 May, and 7 May, in 2004, 2005 and 2006, respectively. A no-till drill

Table 1 Soil characteristics of the experimental sites, Saskatchewan, Canada

Location	Latitude/longitude/ elevation	USA soil description	Canadian soil classification	Texture				Organic matter	pH (water paste)
				Class	Sand (Percent)	Silt	Clay		
Indian Head	50°32' N; 103°40' W; 580 m	Typic Haplustoll	Indian Head (heavy clay)	Clay	18	39	43	8.3	6.7
Swift Current	50°15' N; 107°44' W; 817 m	Aridic Haploboroll	Swinton (silt loam)	Silt loam	23	49	28	3.0	7.3

with hoe openers and row packers at the row spacing of 20 cm (Indian Head) and 25 cm (Swift Current) was used for seeding. The plot size was 2.4×10.7 m at Indian Head, and 2×14 m at Swift Current. The seeding rate was based on seed size, pre-seeding germination rate, and estimated field emergence rate of 70% to target a plant population of 120 plants per square meter.

At each environsite, barley crop was fertilized with urea which was mid-row banded 6-cm deep along with mono-ammonium phosphate (11–51–0 of N–P_2O_5–K_2O), and all plots received the same rate of fertilizers (Table 2). The blanket application of fertilizers to all barley plots at each environsite allowed the determination of the potential effect of various rates of N fertilizer applied to the previous oilseed crops. At all sites, barley crops were grown using no-till management practices, where all fertilizers were applied at the time of sowing the crop in a single operation. Weed control in barley was achieved using a pre-seeding or a pre-emergent burn-off treatment of glyphosate at 1.2 Lha^{-1} of active ingredient (a.i.), along with bromoxynil at 500 mL ha^{-1} and MCPA ester at 500 mL ha^{-1} plus 2,4-D 600 Amine at 910 mL ha^{-1}. At physiological maturity, aboveground plant biomass was determined by harvesting plants in a 1.0-m^2 area in each plot, and the plant samples were oven-dried at 70°C for 7 to 10 days and weighed. At full maturity (grain moisture approaching 130 gkg^{-1}), entire plots were harvested with a plot harvester and grain dry weight determined. The N concentration in the straw was determined using the standard Kjeldahl N method. Root dry weight was estimated using the model developed by Gan et al. (2009), where root biomass was a proportion of straw biomass at a given growing condition.

2.2 Estimates of GHG emissions and carbon footprint

Barley carbon footprint is largely dependent on (1) grain yield of the crop and (2) total greenhouse gas (GHG) emissions associated with the crop production, including CO_2 emissions from energy use and N_2O emissions from non-energy sources. The CO_2 emission associated with urea fertilizers applied to the barley crop was also included. Using site-collected data for each of the six environsites coupled with empirical modeling, we estimated the GHG emissions deriving from (1) application of synthetic N and P fertilizers; (2) crop residue decomposition; (3) production, storage, and transportation of synthetic N and P fertilizers to the farm gate; (4) production of herbicides and pesticides and their applications; and (5) various farming operations such as spraying pesticides during the crop production year, planting and harvesting the crop. The system boundaries were set as the period of the life cycle from production inputs (such as fertilizers, pesticides, seeds), delivery of the inputs to farm gates, and the barley crops were harvested and the grain products stored in bins on the farm. Potential emissions along the logistics of transporting, exporting, or marketing the grain products leaving from the farm were not considered in this study because they were considered the same for all crop management practices evaluated in this study.

It is generally known that N_2O as a by-product is produced during nitrification and denitrification by microorganisms (Forster et al. 2007). The amount of direct and indirect N_2O emissions is related to the quantity of N applied along with environmental conditions (Dyer et al. 2010). The magnitude of these emissions has been studied for the Canadian

Table 2 Monthly precipitation, potential evapotranspiration (PE), fertilization, estimated fraction of N subject to leaching and calculated direct N_2O emission factors for synthetic N application and crop residue decomposition at Indian Head in 2005, 2006, and 2007 and at Swift Current in 2004, 2005, and 2006, Saskatchewan, Canada

Variable		Indian Head			Swift Current		
		2005	2006	2007	2004	2005	2006
Precipitation (mm)	May	57.6	39.0	81.2	83.7	22.4	43.5
	June	99.2	80.4	47.1	66.2	123.2	99.9
	July	59.2	4.4	51.4	61.1	21.4	26.3
	August	98.0	11.8	67.9	72.3	52.1	24.1
	September	4.0	61.7	24.4	27.4	40.7	25.0
	October	6.6	71.7	30.0	21.5	9.2	8.8
	Total	324.6	269.0	302.0	332.2	269.0	227.6
PE (mm)		554.4	615.9	597.7	520.2	561.9	620.7
Fertilizer N applied to barley (kg Nha^{-1})		56	45	62	35	30	35
Fertilizer P applied to barley (kg P ha^{-1})		25	21	23	14	17	22
Emission factor for N_2O		0.0070	0.0050	0.0062	0.0092	0.0057	0.0033
$FRAC_{LEACH}$[a]		0.1495	0.1197	0.1374	0.1827	0.1307	0.0944

[a]N leaching factor

conditions (Gregorich et al. 2005; Rochette et al. 2008). Using a large number of experimental observations on measured N_2O fluxes from Canadian farmlands, Rochette et al. (2008) developed a simple and accurate model for determining N_2O emission factors based on a growing season moisture deficit—a linear function of the ratio of growing season precipitation (P) to potential evapotranspiration (PE) as follows:

$$EF = 0.022\,P/PE - 0.0048, \tag{1}$$

where EF is the emission factor with a unit of kilogram N_2O–N per kilogram of N; P/PE is the ratio of P to PE during the growing season (1 May–30 Oct) based on long-term data (see Table 2). Soil mineral N, particularly in the form of nitrate, in the rooting zone is subject to leaching, and this N can be leached or has undergone further transformations to emit N_2O. We estimated the fraction of N subject to leaching ($FRAC_{LEACH}$) as follows:

$$FRAC_{LEACH} = 0.3247P/PE - 0.0247 \tag{2}$$

Using the method developed by the Intergovernmental Panel on Climate Change (IPCC) adopted for Canadian conditions (IPCC 2006), emissions of N_2O from synthetic N applications were estimated as follows:

$$CO_2eq_{SNF-N20} = Q_{SNF} \times \{(FRAC_{GASM} \times EF_{VD}) + EF + (FRAC_{LEACH} \times EF_{LEACH})\} \times \frac{44}{28} \times 298 \tag{3}$$

where $CO_2eq_{SNF\text{-}N2O}$ was the total emissions from the synthetic N fertilizer application (kilogram CO_2eq per hectare), Q_{SNF} was the quantity of synthetic N fertilizer applied (kilogram N per hectare), $FRAC_{GASM}$ was the fraction of synthetic N fertilizer that volatilized as NH_3^- and NO_x–N ($FRAC_{GASM}$=0.1 kg Nkg^{-1} N), EF_{VD} was the N_2O emission factor for volatilized NH_3^- and NO_x–N (EF_{VD}= 0.01 kg Nkg^{-1} N), EF_{LEACH} was the N_2O emission factor for nitrate leaching (EF_{LEACH}=0.0075 kg Nkg^{-1} N), 44/28 was the conversion coefficient from N_2O-N to N_2O, and 298 was the global warming potential of N_2O over 100 years (IPCC 2006). In the case where urea was applied to the barley crop, the carbon contained in the urea is often released as CO_2 during hydrolysis (IPCC 2006). Thus, emissions of CO_2 from urea-based N fertilizer were calculated as follows:

$$CO_2\,eq_{SNF-CO2} = Q_{SNF-UREA} \times \frac{12}{28} \times \frac{44}{12}, \tag{4}$$

where $CO_2eq_{SNF\text{-}CO2}$ was the emissions of CO_2 from the urea application (kilogram CO_2eq per hectare), $Q_{SNF\text{-}Urea}$ was the quantity of urea-based N fertilizer applied (kilogram N per hectare), 12/28 was the ratio of C to N, and 44/12 was converted C to CO_2. When the barley crop was harvested, straw and roots were returned back to the soil. The N contained in the barley crop residues provided additional source of N for nitrification and denitrification, leading to N_2O emissions. The quantity of barley crop residue N (Q_{CRD}) was obtained using the aboveground and belowground crop residue biomass multiplied by its respective N concentration. Thus, emissions from barley crop residue decomposition were calculated as follows:

$$CO_2\,eq_{CRD} = Q_{CRD} \times \{EF + (FRAC_{LEACH} \times EF_{LEACH})\} \times \frac{44}{28} \times 298 \tag{5}$$

The Haber-Bosch process that converts N_2 and H_2 gases into NH_3 is known to be energy and emission intensive (Gan et al. 2011a). Based on available data from the studies conducted in North America (Lal 2004; Rochette et al. 2008), we estimated emissions from the production, transportation, storage, and delivery of fertilizers to farm fields using an emission factor of 4.8 kg CO_2eq kg^{-1} of N and 0.73 kg CO_2eq kg^{-1} of P_2O_5, multiplied with the amount of N and P fertilizers on a per-hectare basis.

Herbicides and fungicides were used in the production of barley crops. Although emission factors for each individual pesticide are not available at the present time, we assumed that the emission during the process of production, transportation, storage, and field application was similar among pesticides within a similar category. Thus, emissions due to pesticides were estimated based on active ingredient of a fungicide or herbicide product, with the emission factor of 23.1 kg CO_2eq kg^{-1} of a.i. for herbicides and 14.3 kg CO_2eq kg^{-1} of a.i. for fungicides. The emissions associated with various farming operations such as sowing, spraying, and harvesting were estimated using a factor of 14 kg CO_2eq ha^{-1} for no-till planting, 5 kg CO_2eq ha^{-1} for herbicide and fungicide spraying, and 37 kg CO_2eq ha^{-1} for harvesting (Lal 2004; Gan et al. 2011b).

With the above factors, we estimated (1) total GHG emissions per unit of areas for the production of barley, expressed as kilogram CO_2eq per hectare and (2) carbon footprint as emissions per kilogram of barley grain produced under the specific growing conditions, expressed as kilogram CO_2eq per kilogram of grain.

2.3 Statistical analysis

Data were analyzed using the PROC MIXED model of SAS (Littell et al. 1996), where oilseed crop type of the previous year and fertilizer N rate applied to the previous oilseeds were designated as fixed effects and replicates as random effects. In the analysis, N fertilizer was considered a class

variable, whereas the various N rates received by previous oilseeds was considered a continuous variable. Therefore, all interactive responses of crop types and environsites to the various N rates were determined by performing linear and nonlinear regressions in the analysis of variance. Following the ANOVA analysis, covariance analysis was performed to determine the possible main factors contributing to the variance observed in emissions and carbon footprint of barley. Residual soil mineral N in the 0–60-cm depth prior to seeding was treated as a covariable in the analysis. In all analyses, significant effects were declared at $P<0.05$.

3 Results

3.1 Productivity of previous oilseeds and re-cropped barley

Detailed results on the biomass, seed yield, and quality of the four oilseed species grown the previous year have been discussed in a previous publication (May et al. 2010). To facilitate the carbon footprint estimate of the subsequent barley crop, we presented a summary of the productivity of oilseed crops. In brief, all four oilseed species had a curvilinear increase in seed yield as fertilizer N rates increased from 0 to 200 kg Nha^{-1}, with the largest yield response observed in *B. napus* canola to the high end of N rates. The majority of the increase in flax seed yield occurred as the N rate increased from 10 to 90 kg ha^{-1}, while most of the increase in seed yield of *B. juncea* canola and sunflower occurred as N rates increased from 10 to 70 kg ha^{-1}. For all oilseeds tested, their protein concentration increased but oil concentration decreased as the N rate increased. With the current available cultivars in each species, *B. napus* hybrid canola produced the greatest oilseed yield and required the highest N input.

The grain yield of barley crops differed significantly among environsites (Fig. 1a). Barley grown at Indian Head in 2005 produced the highest yield (4,682 kg ha^{-1}), whereas the barley at Swift Current in 2005 yielded the lowest (1,368 kg ha^{-1}). Barley grain yield was also influenced significantly by crop species grown the previous year (see Fig. 1a), but the majority of the differences was due to sunflower crops which resulted in the lowest grain yield of barley in most environsites, except at Swift Current in 2006 where no differences were found. Overall, the barley preceded by flax, canola, and juncea crops produced similar grain yields at four of six environsites, with the barley preceded by canola at Indian Head in 2006 and Swift Current in 2005 having greater grain yields than being preceded by the other oilseed species.

The grain yield of barley crops was linearly related to the amount of fertilizer N applied to the previous oilseeds (see Fig. 1b). Increasing rate of fertilizer N applied to the

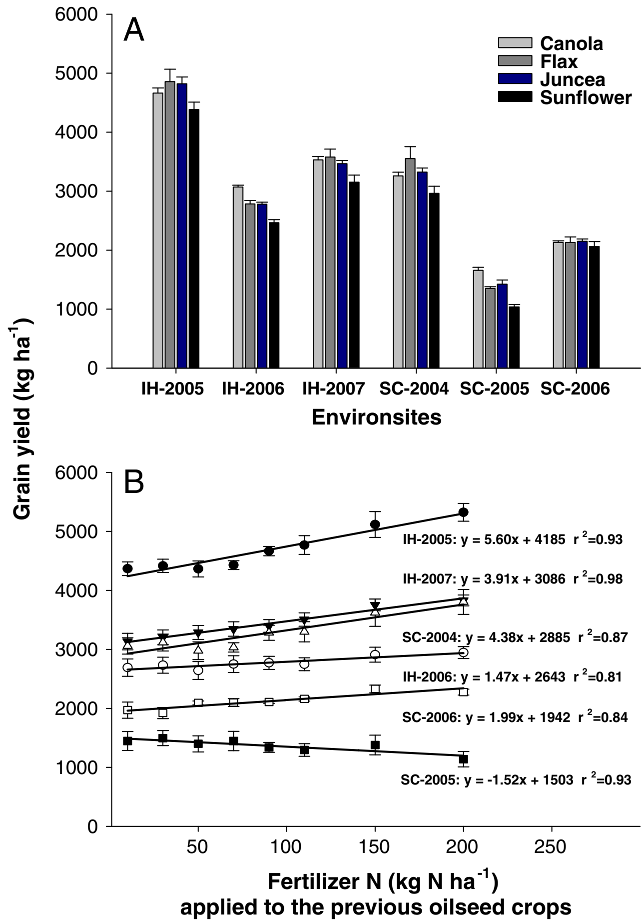

Fig. 1 Average grain yield of barley crop **a** that was preceded by different oilseed crops (across all N rates) at Indian Head (*IH*) in 2005, 2006, and 2007 and at Swift Current (*SC*) in 2004, 2005, and 2006 and **b** in relation to the rate of N fertilizer applied to the previous four oilseed crops, in Saskatchewan, Canada. *Bars* are standard errors

previous oilseed crops significantly increased the grain yield of succeeding barley crops at all environsites except at Swift Current in 2005. The magnitude of the yield response was interacted with environsites; every 1 kg of fertilizer N applied to the previous oilseeds increased barley grain yield by 5.6 kg at Indian Head in 2005, 4.4 kg at Swift Current in 2004, 3.9 kg at Indian Head in 2007, 2.0 kg at Swift Current in 2006, and 1.4 kg at Indian Head in 2006, but decreased by 1.5 kg at Swift Current in 2005.

3.2 Main contributors of emission estimates in barley

The long-term (1971–2010) average growing season (1 May–31 Oct) precipitation was 264 mm at Swift Current and 317 mm at Indian Head, and PE was 635 mm at Swift Current and 605 mm at Indian Head. Using Eq. 1, we estimated that direct emission factors for soil N_2O from synthetic N application and crop residue decomposition were 0.0067 kg N_2O–N kg^{-1} N at Indian Head and

0.0044 kg N_2O–N kg^{-1} N at Swift Current. On a relative basis, the direct emission factor at Indian Head was about 50% greater than that at Swift Current. However, weather conditions varied widely among environsites during the course of the experiment (see Table 2). The most noticeable is that at Indian Head, the growing season precipitation was higher, but the PE was lower than the long-term average in 2005. The opposite was true in 2006 while the 2007 growing season precipitation and PE were near the long-term average. At Swift Current, the growing season precipitation was greater, but the PE was lower than the long-term average in 2004. As a result, the estimated direct N_2O emission factor for 2004 at Swift Current was 0.0092 kg N_2O–N kg^{-1} N, the highest among all environsites. In 2006, lower than the long-term average growing season precipitation and average PE at Swift Current resulted in the lowest direct N_2O emission factor (0.0033 kg N_2O–N kg^{-1} N) among all environsites.

Many factors contributed to the GHG emissions in the production of barley crops. Covariance analysis revealed that 89% of variance in GHG emissions was due to growing environments (Table 3). Nitrogen fertilizer applied to the previous oilseeds contributed 7% of the variation in the total GHG emissions, and the other factors, albeit being important to barley production, contributed little to the variation of total emissions. Overall, environsites had a highly significant effect on total emission (see Table 3). Averaged across the four oilseed species grown the previous year, the succeeding barley crop grown at Indian Head emitted GHGs of 1,003 kg CO_2eq ha^{-1}, or 53% greater than the emission of barley crop grown at the drier Swift Current site (Table 4). Even at the same experimental site, total emissions differed significantly between years mainly due to precipitation and evapotranspiration. At Indian Head, the 2005 barley crop had total emissions 52% greater than the 2006 barley crop, whereas at Swift Current, the 2006 barley crop had total emission 32% less than the 2004 barley crop.

Nitrogen, phosphorous, and pesticides are the main inputs in the production of barley crops. Estimated emissions from the production, transportation, storage, and delivery of inorganic fertilizers to the farm gate accounted for an average of 26% of the total emissions (see Table 4), and the direct and indirect emissions from the application of N fertilizer to the barley crop added another 28%. Thus, the production and application of synthetic N together contributed 53% of the total emissions. Such a proportion (i.e., fertilizer-N-related emissions in the total emission) was nearly the same across all environsites, even though the absolute emission values varied largely among environsites. For example, the emission due to the application of N fertilizer was 129 kg CO_2eq ha^{-1} at Swift Current in 2006 but was 350 kg CO_2eq ha^{-1} at Indian Head in 2007. Averaged across the six environsites, the GHG emissions due to the use of fertilizer-N was 26.6 times the emission from the use of phosphorous, 5.2 times the emission from pesticide supply, and 4.2 times the emission from various farming operations.

The decomposition of barley crop residues contributed direct and indirect emissions, averaging 173 kg CO_2eq ha^{-1}, or 19% of the total emission (see Table 4). This portion of the emission varied among environsites, largely due to the variation in the amount of barley straw and root biomass and the difference in P/PE ratio. For example, the barley grown at Indian Head in 2005 produced 6,720 kg ha^{-1} of straw and 2,620 kg ha^{-1} of roots, resulting in the highest emission from

Table 3 Summary of covariance of analysis for total emissions and carbon footprint for barley grown at various previous rates of N fertilizer at eight environmental sites (location–year combinations) in Saskatchewan, Canada

Source	DF	Total GHG emission in the production of barley crops		Carbon footprint of barley crops	
		Sum of squares	% variance	Sum of squares	% variance
Environsites	5	8,656,697	**88.7**	1.0750	**72.0**
Preceding crop type	18	124,322	1.3	0.1741	**11.7**
N rates in previous crops[a]	1	669,688	**6.9**	0.0324	**2.2**
N × N	1	38,028	0.4	0.0068	0.5
Nitrogen[a]	5	1,678	0.0	0.0046	0.3
C × Env[b]	5	95,472	1.0	0.1237	**8.3**
N × N × Env	5	13,259	0.1	0.0095	0.6
Env × nitrogen	25	9,192	0.1	0.0068	0.5
Seed yield of barley	1	57,552	0.6	0.0123	0.8
Residual soil mineral N at seeding	1	89,863	0.9	0.0195	1.3
Crop residues of barley	1	1,240	0.0	0.0019	0.1
Residual	122	0	0.0	0.0264	1.8

Bold numbers represented that the effect was significant at $P<0.05$

[a] In the covariance analysis, N rate was considered as a continuous variable, whereas nitrogen was consider as a 'class' factor

[b] *Env* environsites, *C* preceding crop type, *N* N rates in previous crops

Table 4 Average grain yield, total emissions and emissions due to N fertilization, crop residue decomposition, pesticide use, and various farming operations, as well as the carbon footprint of barley crops grown in Saskatchewan, Canada

Location	Year	Grain yield of barley (kg ha^{-1})	Total emission (kg CO_2eq ha^{-1})	Emission from N fertilizer production		Emission from N fertilizer application		Emission from production and application of N	Emission from crop residue decomposition		Emission from production and supply of pesticides		Emission due to various farming operations		Carbon footprint (kg CO_2eq kg^{-1}) of seed
				kg CO_2eq ha^{-1}	Percent	kg CO_2eq ha^{-1}	Percent	Percent	kg CO_2eq ha^{-1}	Percent	kg CO_2eq ha^{-1}	Percent	kg CO_2eq ha^{-1}	Percent	
Indian Head	2005	4,682[a]	1,175	267	23	350	30	53	347	29	110	9	101	9	0.252
	2006	2,774	774	215	28	205	26	54	126	16	107	14	122	16	0.281
	2007	3,433	1,059	296	28	333	31	59	201	19	108	10	122	12	0.311
Swift Current	2004	3,274	834	166	20	240	29	49	226	27	102	12	101	12	0.257
	2005	1,368	563	143	25	150	27	52	72	13	104	18	94	17	0.426
	2006	2,119	565	167	30	129	23	52	67	12	108	19	94	17	0.268

[a] Averaged across all treatments

the crop residue decomposition at 347 kg CO_2eq ha^{-1}, or 5.1 times the same category of emissions by the barley crop grown at Swift Current in 2006.

Emissions associated with pesticide use and various farming operations in the production of barley crops were lower than the emission from the use of N fertilizers (see Table 4). The barley crop received a pre-seeding burn-off treatment with glyphosate plus two in-crop applications of herbicides, one for grassy weed control and the other for broadleaf weed control.

3.3 Carbon footprint versus preceding crops and N rates

Covariance analysis revealed that the carbon footprint of barley crop was significantly influenced by the choice of oilseeds grown in the previous year (see Table 3). At Swift Current in 2005, when the barley was preceded by sunflower, it had a significantly higher carbon footprint than when preceded by other oilseed crops (Fig. 2). Sunflower is a deep-rooting crop which depleted soil water throughout the profile. As a result, barley grown after sunflower decreased grain yield by an average of 23% compared with barley grown after flax, 37% decrease compared with barley after *B. juncea* canola, and 59% decrease compared with barley after *B. napus* canola (Fig. 1a). The significant effect of previous oilseed types on the grain yield of re-cropped barley led to the significant differences in its carbon footprint.

Both emissions and carbon footprint of barley crop also were significantly influenced by the rate of N fertilizer applied to the previous oilseeds (see Table 3). More N fertilizer applied to the previous oilseeds gave rise to greater GHG emissions in the subsequent barley crop. At all environsites, the amount of residual soil mineral N measured prior to seeding the barley crop was increased as the amount of N applied to the previous oilseeds more than 90 kg N ha^{-1}

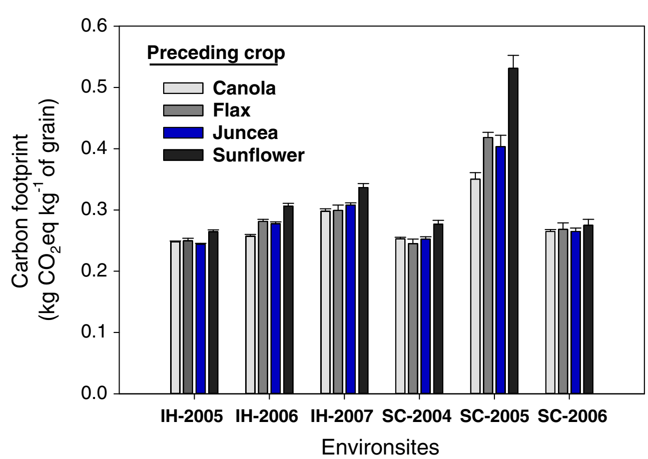

Fig. 2 Carbon footprint of barley crop preceded by different oilseed crops (averaged across N rates) at six different environmental sites in Saskatchewan, Canada. *Bars* are standard errors

(Fig. 3a). This effect was consistent for all the oilseed species evaluated (see Fig. 3b). Regression analysis showed that total emission in the production of barley crop was a linear function of the rate of fertilizer N applied to the previous oilseeds at four of the six environsites (Fig. 4a). At those environsites, increased N fertilizer application to the previous oilseeds increased the total emission of the subsequent barley crops. This was largely due to the greater amounts of straw and roots (data not shown) produced by barley crops grown in the high-N soil, causing more GHG emission from the decomposition of the barley resides. The relationship between N rates applied to the previous oilseed crops and the emission of the subsequent barley crops was consistent across various environsites (see Fig. 4a).

3.4 Carbon footprint versus environments

Covariance analysis revealed that the carbon footprint of barley differed significantly among environsites; 72% of the variation in the barley carbon footprint was due to environments (see Table 3). The barley grain produced at Swift Current in 2005 had the highest carbon footprint at 0.426 kg CO_2eq kg^{-1} of grain, 70% greater than the carbon

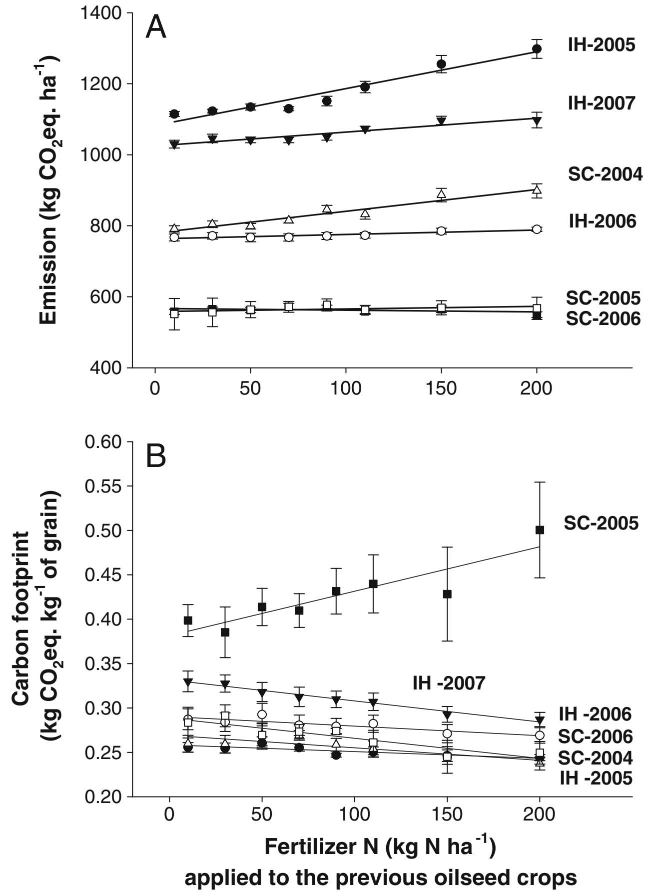

Fig. 4 The effect of the rate of fertilizer N applied to the previous oilseed crops on **a** the greenhouse gas emissions and **b** the carbon footprint of the subsequent barley crop at Indian Head (*IH*) in 2005–2007 and at Swift Current (*SC*) in 2004–2006. *Bars* are standard errors

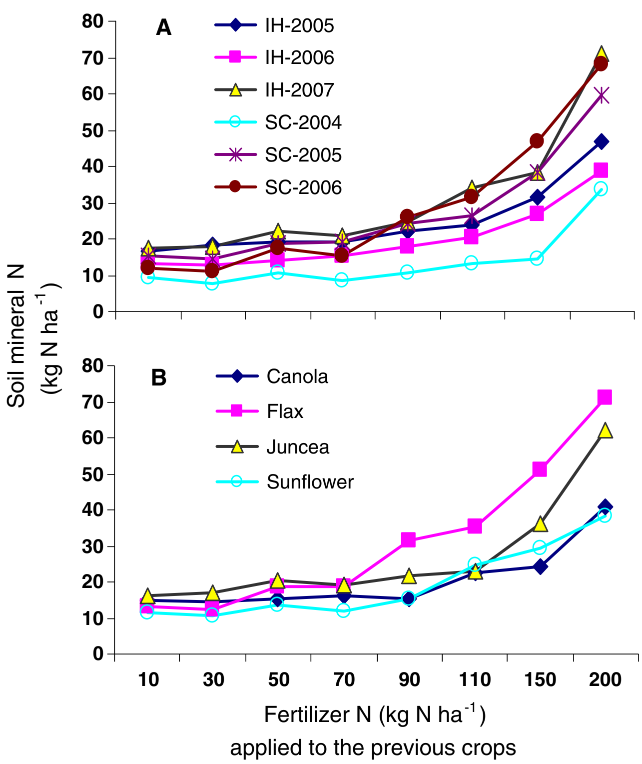

Fig. 3 The relationship between the rates of fertilizer N applied to the previous oilseed crops and the residual soil mineral N (NH_4^+ and NO_3^-) in the 0–60-cm depth measured prior to the seeding of barley **a** at various site-years and **b** on the fields with different oilseed crops the previous year

footprint value of the barley produced at Indian head in 2005 (0.252 kg CO_2eq kg^{-1} of grain) (see Table 4). On average, Swift Current-produced barley had about 11% greater carbon footprint than Indian Head-produced barley (0.317 vs. 0.281 kg CO_2eq kg^{-1} of grain). Although total emissions associated with the barley production at Indian Head were generally greater than the emission at Swift Current, the barley produced at Indian Head had significantly greater grain yield. Carbon footprint was a function of grain yield and total GHG emissions. Increasing grain yield decreased carbon footprint in barley, and the magnitude of the decrease depended on total GHG emissions.

The relationship between N rate received by the previous oilseed crops and the carbon footprint of the subsequent barley crops was significantly altered by environments (see Fig. 4b). At Swift Current in 2005, the increased N rates to the previous oilseeds significantly increased barley carbon footprint; the opposite was true at Indian Head in 2006 when the increased N rates to the previous oilseeds significantly decreased barley carbon footprint; at the other environsites,

the barley carbon footprint did not change with the N rate of the previous oilseeds. The large variation in barley carbon footprint between environsites was a result of the different magnitudes of responses of grain yield (see Fig. 1b) and the total emission (see Fig. 4a) to the rate of N applied to the previous oilseed crops. At a given N rate, the barley grown at Swift Current in 2005 had its carbon footprint significantly greater than the values at the other environsites. In that particular year, high rainfall in the month of June (see Table 2) caused excessive vegetative growth in barley, but severe drought occurred in July prevented the photosynthetic materials from being remobilized into grain sinks, resulting in low seed yield (see Fig. 1).

4 Discussion

4.1 Estimation methodology and main contributors to barley carbon footprint

Total GHG emissions associated with the production of barley crops included CO_2 emissions from energy use and N_2O emissions from non-energy sources. To estimate the total emission accurately, we measured various emission contributors from the site-specific plot experiment with an approach similar to that used previously (Rochette et al. 2008; Gan et al. 2011b). Also, we employed the IPCC methodology (IPCC 2006) adopted for Canadian conditions (Rochette et al. 2008) to establish the emission factors of each emission contributor. We feel that the approach of taking the site-specific measurement combined with adopting empirical relationships is quite effective in evaluating the impact of farming practices on the carbon footprints of field crops.

Synthetic N fertilizers used in the production of barley crops contributed the greatest percentage (53%) of the total emissions. Of which about 28% of the emission came from direct and indirect emissions of N_2O from the application of N fertilizers in the field, and the other 26% coming from the production, transportation, storage, and delivery of N fertilizers to farm gates prior to farm use. When barley crop was harvested, the straw and roots were returned back to the field under no-till management practices. These plant litters served as an important N source for nitrification and denitrification, contributing directly and indirectly to N_2O emissions. In our study, the decomposition of barley straw and roots contributed an average of 19% to the total emission. In a previous study, Gan et al. (2011c) reported that straw and roots in durum wheat contributed about 25% of its carbon footprint, whereas the decomposition of oilseed straw and roots contributed about 10% of the total carbon footprint (Gan et al. 2011b). The large difference between oilseeds and cereals is because the cereals have greater amounts of straw and root C (typically >2,200 kg $\mathrm{C\,ha^{-1}}$) than oilseeds (typically <1,700 kg $\mathrm{C\,ha^{-1}}$) under similar growing conditions. Also, the magnitude of the contribution from the decomposition of crop residues is related to the net productivity of a crop (Forster et al. 2007), N concentrations of the plant residue (Janzen et al. 2006), and growing conditions such as soil moisture and temperature (Flynn et al. 2005; Merrill et al. 2007).

4.2 Barley carbon footprint versus cropping practices

Under a specific environment, the GHG emission in the production of barley crop was influenced by preceding crop species and N fertilization applied to the previous crops. Sunflower grown in the semiarid area depleted soil moisture in the deeper layers (Angadi and Entz 2002), decreased grain yield of the subsequent barley crops, and increased barley carbon footprint. At most environsites evaluated, the total emission of barley crops was linearly associated with the amount of N fertilizer applied to the previous oilseeds. The higher the N fertilizer applied to the previous crops, the greater the emission the subsequent barley crop. Fertilizer N applied to the previous oilseeds at the rate greater than 90 kg $\mathrm{N\,ha^{-1}}$ significantly increased the GHG emission of the succeeding barley. The oilseed crops grown the previous year had little or no response to fertilizer N greater than 90 kg $\mathrm{N\,ha^{-1}}$ (May et al. 2010), and the left, unused N increased the amount of residual soil mineral N significantly (see Fig. 3). The residual soil mineral N had a positive effect on barley straw and root biomass and thus increasing total emissions.

However, higher GHG emissions in barley production due to N fertilization or preceding crops did not always mean a higher carbon footprint, depending on whether or not the cropping practices resulted in greater grain yields. Increased grain yield decreased the carbon footprint of barley significantly, and the magnitude of the change in carbon footprint depended on total GHG emissions. This was the case in our study that at Swift Current in 2005, the increased N fertilization to the previous oilseeds significantly increased GHG emission, but the grain yield of the succeeding barley crop was negatively affected by drought which occurred during the reproductive growth period, resulting in the high carbon footprint of barley. In contrast, at Indian Head in 2006, the increased N fertilization to the previous oilseeds significantly increased both GHG emission and grain yield, but the yield increase was more substantial than the GHG increase, thus lowered the carbon footprint of barley. Our finding was in agreement with van Groenigen et al. (2010) who used the term yield-scaled N_2O emissions as N_2O emissions per unit of grain yield. Our study indicates that the key to lower the carbon footprint of barley crops is to increase grain yield and improve N use efficiency. It can be reasonably

expected that all cropping practices that help increase grain yields and improve N use efficiency will lower the carbon footprint of the crop.

4.3 Potential limitations

In barley production, the most significant emission related to the energy use is the production of synthetic N fertilizers, accounting for about 28% of the total emissions. The production of pesticides contributed a similar amount of emissions as various farming operations, each accounting for about 14% of the total emission. Thus, more than 53% of the total emissions for barley production were directly related to the on-farm and off-farm energy use. In contrast, emissions due to fossil CO_2 was very low in barley production, and the potential impacts of cropping practices on fossil CO_2 emissions were assumed the same in the present study because the treatments evaluated in our plot study did not cause large differences in fossil CO_2 emissions. However, there are other terms in the farm energy budget such as gasoline consumption for on-farm/farm-owned transport, manufacture and supply of farm machinery, heating fuels (natural gas), and farm electrical power, among others. We were unable to measure those energy terms due to the small scale of the plot study, therefore, the estimated carbon footprint values mainly showed how cropping management practices affected the carbon footprint of barley and did not intend to be a complete value. Also, the exact amount of emissions might change slightly if those un-measured energy terms were considered, although adding those on-farm fuel uses will unlikely change the overall conclusions of the present study.

The method used in estimating emissions of N_2O from synthetic N application and crop residue decomposition in the study was primarily based on the methodology of Rochette et al. (2008) who used many years of field flux measurements of N_2O at Swift Current, the site where the present study was conducted. In our calculation, a generic NH_3 release rate was used according to IPCC recommendation although the NH_3 emissions may differ between N fertilizers, and indirect emissions (such as N_2O from NH_3 or CO_2 from CO) were not taken into account. Also, carbon change in the soil due to crop residues was not considered in our calculation of carbon footprint; this followed the guideline of PAS 2050 (BSI and Carbon Trust 2011) where it is indicated that the assessment of emission must include GHG emissions arising from direct land use change but must not include those arising from soil carbon changes in existing agricultural systems.

Furthermore, the relationships among soil and climatic environments, as agronomic practices and N_2O emissions are complex (Osborne et al. 2010). Emissions of CO_2, N_2O, and CH_4 are often complicated by crop, water management, biogeochemical characteristics of soil (i.e., pH, salinity, C/N ratio, bulk density, redox potential), microbial community, weather, soil fertility status, and crop management practices. These diverse factors and their relationships to gas productions make it complex and difficult to generalize. While the model and the IPCC method to estimate CO_2eq were tested on many Canadian farms, these models might not the best describing seasonal and temporal variations of GHG emissions in barley production. Nevertheless, we believe that the findings on the effect of the specific cropping practices (the choice of oilseed species and the rate of N fertilization applied to the oilseeds) on the carbon footprint of barley was novel and valuable for land management and modelers who are interested in lowering the carbon footprints of field-grown crops.

5 Conclusions

More than 70% of the variation in the estimated carbon footprint of barley was caused by environments. On average, Indian Head-produced barley had a carbon footprint of 0.281 kg CO_2eq kg^{-1} of grain, significantly lower (11%) than Swift Current-produced barley (0.317 kg CO_2eq kg^{-1} of grain); this was largely because the barley produced at Indian Head had significantly higher grain yield than the same crop produced at Swift Current. Nitrogen fertilization in the barley production contributed more than 50% of the total GHG emission. Increasing N fertilizer to the previous oilseed crops significantly increased the GHG emission of the succeeding barley crops, suggesting that it is possible to shift emissions from one crop to another within a crop rotation sequence. The carbon footprint of barley was a function of grain yield and total GHG emissions; increased grain yield decreased the carbon footprint, and the magnitude of the change depended on the value of total GHG emissions. The key to lower the carbon footprint of barley is to increase barley grain yield through best crop management practices such as optimizing N fertilizer input and maximizing N use efficiency. The present study had the system boundary set from the production of inputs, the delivery of inputs to farm gates, and the barley grain harvested. A full life cycle assessment may be required to estimate carbon footprints for a whole production–marketing chain or under various choices of boundaries; this can be achievable in the near future as more advanced scientific tools are becoming available.

Acknowledgments We gratefully acknowledge the excellent technical assistance provided by Cal McDonald, Lee Poppy, and Ray Leshures at Swift Current and Roger Geremia, Orla Willoughby, and Randy Shiplackand at Indian Head for conducting the field experiments, and the funding provided by Saskatchewan Canola Development Commission and the Matching Investment Initiative of Agriculture and Agri-Food Canada. We also thank Mr. Dirk Anderson for providing annual estimates of the growing season potential evapotranspiration rates for the experimental sites.

References

Angadi SV, Entz MH (2002) Agronomic performance of different stature sunflower cultivars under different levels of interplant competition. Can J Plant Sci 82:43–52

Brandt SA, Malhi SS, Ulrich D, Lafond GP, Kutcher HR, Johnston AM (2007) Seeding rate, fertilizer level and disease management effects on hybrid versus open pollinated canola (*Brassica napus* L). Can J Plant Sci 87:255–266

BSI and Carbon Trust (2011) Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. Publicly available specification - PAS 2050:2011. ISBN 978 0 580 71382 8. London, UK. pp 36

Intergovernmental Panel on Climate Change 2006 (2006) IPCC Guidelines for national greenhouse gas inventories vol 4. Agriculture, forestry and other land use, intergovernmental panel on climate change, Paris, France www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html. Accessed Apr 20 2011

Cutforth H, McConkey B, Brandt S, Gan Y, Lafond G, Angadi S, Judiesch D (2009) Fertilizer N response and canola yield in the semiarid Canadian prairies. Can J Plant Sci 89:501–503

Dyer JA, Vergé XPC, Desjardins RL, Worth DE, McConkey BG (2010) The impact of increased biodiesel production on the greenhouse gas emissions from field crops in Canada. Ener Sust Dev 14:73–82

Flynn HC, Smith J, Smith KA, Wright J, Smith P, Massheder J (2005) Climate- and crop-responsive emission factors significantly alter estimates of current and future nitrous oxide emissions from fertilizer use. Glob Chang Biol 11:1522–1536

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, pp 129–234

Gan YT, Campbell CA, Jansen HH, Lemke R, Liu LP, Basnyat P, McDonald CL (2009) Carbon input to soil by oilseed and pulse crops in semiarid environment. Agric Ecosyst Environ 132:290–297

Gan YT, Kutcher R, Menalled F, Lafond L, Brandt S (2010) Crop diversification and intensification with broadleaf crops in cereal-based cropping systems in the Northern Great Plains of North America. In: Malhi SS, Gan YT, Schoenau JJ, Lemke RL, Liebig MA (eds) Recent trends in soil science and agronomy research in the Northern Great Plains of North America. Research Signpost, Kerala, p 427

Gan Y, Liang BC, Hamel C, Cutforth H, Wang H (2011a) Strategies for reducing the carbon footprint of field crops for semiarid areas. A review. Agron Sust Dev 31(4):643–656

Gan Y, Liang L, Huang G, Malhi SS, Brandt SA, Katepa-Mupondwa F (2011b) Carbon footprint of canola and mustard is a function of the rate of N fertilizer. Int J Life Cycle Assess 17(1):58–68

Gan YT, Liang BC, Wang XY, McConkey BG (2011c) Lowering carbon footprint of durum wheat through diversifying cropping systems. Field Crops Res 122:199–206

Gregorich EG, Rochette P, VandenBygaart AJ, Angers DA (2005) Greenhouse gas contributions of agricultural soils and potential mitigation practices in eastern Canada. Soil Till Res 76:1–20

Janzen HH, Angers DA, Boehm M (2006) A proposed approach to estimate and reduce net greenhouse gas emissions from whole farms. Can J Soil Sci 86:401–418

Karamanos RE, Goh TB, Flaten DN (2007) Nitrogen and sulphur fertilizer management for growing canola on sulphur sufficient soils. Can J Plant Sci 86:201–210

Karamanos R, McKenzie RH, Gan YT, Lafond GP, Jones CA, Malhi SS (2010) Fertilizer management for maximum yield of common crops in the Northern Great Plains of North America. pp 33–72. In: Malhi SS, Gan YT, Schoenau JJ, Lemke RL, Liebig MA (eds) Recent trends in soil science and agronomy research in the Northern Great Plains of North America. Research Signpost, Kerala, p 427

Krupinsky JM, Bailey KL, McMullen MP, Gossen BD, Turkington TK (2002) Managing plant diseases risk in diversified cropping systems. Agron J 94:198–209

Lal R (2004) Carbon emission from farm operations. Environ Int 30:981–990

Liebig MA, Tanaka DL, Krupinsky JM, Merrill SD, Hanson JD (2007) Dynamic cropping systems: Contributions to improve agroecosystem sustainability. Agron J 99:899–903

Littell RC, Milliken GA, Stroup WW, Wolfinger RD (1996) SAS System for mixed models. SAS Institute, Cary

Malhi SS, Brandt SA, Ulrich D, Lafond GP, Johnston AM (2007) Comparative nitrogen response and economic evaluation for optimum yield of hybrid and open pollinated canola. Can J Plant Sci 87:449–460

May WE, Brandt SA, Gan YT, Kutcher HR, Holzapfel CB, Lafond GP (2010) Adaptation of oilseed crops across Saskatchewan. Can J Plant Sci 90:667–677

Merrill SD, Tanaka DL, Krupinsky JM, Liebig MA, Hanson JD (2007) Soil water depletion and recharge under ten crop species and applications to the principles of dynamic cropping systems. Agron J 99:931–938

O'Donovan JT, McAndrew DW, Thomas AG (1997) Tillage and nitrogen influence weed populations dynamics in barley (*Hordeum vulgare* L). Weed Technol 11:502–509

Osborne B, Saunders M, Walmsley D, Jones M, Smith P (2010) Key questions and uncertainties associated with the assessment of the cropland greenhouse gas balance. Agric Ecosyst Environ 139:293–301

Rochette P, Worth DE, Lemke RL, McConkey BG, Pennock DJ, Wagner-Riddle C, Desjardins RL (2008) Estimation of N_2O emissions from agricultural soils in Canada: I–Development of a country-specific methodology. Can J Soil Sci 88:641–654

van Groenigen JW, Velthof GL, Oenema O, van Groenigen KJ, van Kessel C (2010) Towards an agronomic assessment of N_2O emissions: a case study for arable crops. Eur J Soil Sci 61:903–913

Weinheimer J, Rajan N, Johnson P, Maas S (2010) Carbon footprint: a new farm management consideration in the Southern High Plains. In: Agricultural & Applied Economics Association 2010, AAEA, CAES & WAEA Joint Annual Meeting, Denver, CO, USA, July 25–27, 2010

Wiedmann T, Minx J, Barrett J, Wackernagel M (2006) Allocating ecological footprints to final consumption categories with input–output analysis. Ecol Econ 56:28–48

Zentner RP, Campbell CA, Biederbeck VO, Miller PR, Selles F, Fernandez MR (2001) In search of a sustainable cropping system for the semiarid Canadian prairies. J Sust Agric 18:117–136